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THE THERMODYNAMICS OF THE ALUMINUM/ALUMINUM VAPOR SYSTEM

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Rand
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PREFACE

This RAND Memorandum is a continuation of a broad study originally requested in 1962 by the Scientific Advisor to the Physics Division, Research Directorate,* Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico.

It is a contribution to a better understanding of the complex problems involved in the physics of reentry bodies. Aluminum is the eighteenth of a series of ablative materials--and the first metal--to be investigated by means of mathematical techniques similar to those used at RAND in the parametric study of certain low-molecular-weight compounds as nuclear rocket propellants.

The results of the investigation of graphite, polystyrene, polyethylene, phenol-formaldehyde resin, polyamide resin, teflon, silica, zirconia, magnesia, alumina, beryllia, calcia, magnesium silicate, silicon carbide, aluminum silicate, boron carbide, and zirconium nitride, the first seventeen materials to be studied in the series, are reported in the following RAND Memoranda.

RM-3326-3-PR, *The Thermodynamics of the Graphite/Carbon Vapor System*

RM-3708-PR, *The Thermodynamics of the Polystyrene/Hydrocarbon Vapor System*

RM-3709-PR, *The Thermodynamics of the Polyethylene/Hydrocarbon Vapor System*

RM-3988-PR, *The Thermodynamics of the Phenol-Formaldehyde Resin/Carbon-Hydrogen-Oxygen Vapor System*

RM-4404-PR, *The Thermodynamics of the Polyamide Resin (Nylon-6)/Carbon-Hydrogen-Oxygen-Nitrogen Vapor System*

RM-4634-PR, *The Thermodynamics of the Teflon-Fluorocarbon Vapor System*

RM-4804-PR, *The Thermodynamics of the Silica/Silicon-Oxygen Vapor System*

RM-4907-PR, *The Thermodynamics of the Zirconia/Zirconium-Oxygen Vapor System*

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*Now the Air Force Weapons Laboratory.

RM-4943-PR, *The Thermodynamics of the Magnesia/Magnesium-Oxygen Vapor System*

RM-5042-PR, *The Thermodynamics of the Alumina/Aluminum-Oxygen Vapor System*

RM-5151-PR, *The Thermodynamics of the Beryllia/Beryllium-Oxygen Vapor System*

RM-5248-PR, *The Thermodynamics of the Calcia/Calcium-Oxygen Vapor System*

RM-5337-PR, *The Thermodynamics of the Magnesium Silicate/Magnesium-Silicon-Oxygen Vapor System*

RM-5592-PR, *The Thermodynamics of the Silicon Carbide/Silicon-Carbon Vapor System*

RM-5876-PR, The *Thermodynamics of the Aluminum Silicate/Aluminum-Silicon-Oxygen Vapor System*

RM-5958-PR, *The Thermodynamics of the Boron Carbide/Boron-Carbon Vapor System*

RM-6295-PR, *The Thermodynamics of the Zirconium Nitride/Zirconium-Nitrogen Vapor System*

SUMMARY

The purpose of this study is the thermodynamic investigation of aluminum, Al, over a range of temperatures up to 6000°K and pressures up to 10^3 atmospheres.

Two sets of equilibrium composition equations are used--one representing a pure gas phase, the other a heterogeneous system of gas and condensed (i.e., solid or liquid) aluminum. The gas phase of the heterogeneous chemical system, like the homogeneous gas phase, comprises 3 gaseous species.

The results of the computational program are presented in both tabular and graphic form. The latter comprises (a) a conventional Mollier diagram in which specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight or moles of condensed aluminum, (b) a plot of volume versus temperature for aluminum, and (c) a plot of vaporization temperature for aluminum and graphite at various pressures.

ACKNOWLEDGMENTS

This study involved a considerable amount of hand and machine computation. The efforts of the following RAND Physics Department staff members are gratefully acknowledged: Donald A. Brown, for his extensive programming and machine work; Christine A. Skube, for her precise interpolations; and Elizabeth J. Force, for her meticulous graphical presentation of the tabulated results.

CONTENTS

I. INTRODUCTION

This study considers a chemical system that under certain conditions of temperature and pressure is a pure gas mixture and under others is a disperse system, i.e., smoke or fog. In this case the smoke or fog is a gas that contains a condensed phase, solid or liquid aluminum, symbolized by Al.

The following assumptions were made in the computations:

(1) Thermal equilibrium is maintained between the condensed particles and the gas phase.

(2) The pressure due to the thermal motion of the condensed particles can be neglected.

(3) The gas phase obeys the ideal-gas law.

(4) The molar volume of the condensed phase is essentially constant, that is, independent of temperature and pressure.

(5) The volume coefficient of thermal expansion of the condensed phase is constant.

II. COMPOSITION EQUATIONS

In this study it is assumed that the gas formed by heating aluminum, Al, in the absence of a reacting atmosphere at various pressures up to a temperature of 6000°K is a mixture involving three gaseous chemical species--Al, Al^+, and e^---and one condensed species--Al (crystal) or Al (liquid). The presence or absence of a condensed phase makes it necessary to consider two distinct sets of chemical equations.

A. No condensed phase present. In terms of Al and e^- as primary components, the chemical equation for the secondary component, Al^+, is given by the expression

$$Al - e^- = Al^+. \tag{1}$$

The mass-balance equations are

$$n_{Al} = 1 - n_{Al^+} \tag{2}$$

and

$$n_{e^-} = n_{Al^+}, \tag{3}$$

where n_{Al}, n_{e^-}, and n_{Al^+} are the numbers of moles of Al, e^-, and Al^+, respectively, in the system.

In view of Eq. (3), the equilibrium equation is given by the expression

$$n_{Al^+} = [K_{Al^+}(P/n)^{-1} n_{Al}]^{1/2}, \tag{4}$$

where n is the total number of moles of gas in the equilibrium mixture, P is the total pressure in atmospheres, and K_{Al^+} is the thermodynamic equilibrium constant of component Al^+ computed on the basis of Eq. (1).

B. Solid or liquid Al present. In terms of Al (solid or liquid) and e^- as primary components, the secondary components may be obtained from the following chemical equations:

$$\underline{Al} = Al \tag{5}$$

and

$$\underline{Al} - e^- = Al^+. \tag{6}$$

Equations (5) and (6) then yield the following mass-balance equations:

$$n_{\underline{Al}} = 1 - n_{Al} - n_{Al^+} \tag{7}$$

and

$$n_{e^-} = n_{Al^+}, \tag{8}$$

where $n_{\underline{Al}}$, n_{e^-}, n_{Al}, and n_{Al^+} are the numbers of moles of Al, e^-, Al, and Al^+, respectively.

The equilibrium equations are obtained by considering the free energy F of the system and the partial molar free energy, or chemical potential, $\mu_x = \partial F/\partial n_x$ of each component. For an ideal gas

$$\mu_x = \mu_x^o + RT \ln (n_x P/n), \tag{9}$$

where μ_x^o is the chemical potential of component x in the standard state of unit partial pressure, R is the gas constant, T is the temperature, P is the pressure, and n is the total number of moles of gaseous species in the mixture. The chemical potential for Al is given by

$$\mu_{\underline{Al}} = \mu_{\underline{Al}}^o + (P - 1)\bar{v}_{\underline{Al}}, \tag{10}$$

where $\mu^{o}_{\underline{Al}}$ is the standard molar (i.e., gram-atomic) free energy for Al, $\bar{V}_{\underline{Al}}$ is the molar volume of Al, and P is the pressure of the system.

By combining Eqs. (9) and (10), the following expressions are obtained for the derived species Al and Al^{+}:

$$n_{Al} = K_{Al} \exp [(P - 1)\bar{V}_{\underline{Al}}/RT](P/n)^{-1} \tag{11}$$

and

$$n_{Al^{+}} = K_{Al^{+}} \exp [(P - 1)\bar{V}_{\underline{Al}}/RT](P/n)^{-2}(n_{e^{-}})^{-1}. \tag{12}$$

In Eqs. (11) and (12), K_{Al} and $K_{Al^{+}}$ are the thermodynamic equilibrium constants associated with the chemical reactions of Eqs. (5) and (6) and are defined by the relations

$$\mu^{o}_{Al} - \mu^{o}_{\underline{Al}} = - RT \ln K_{Al} \tag{13}$$

and

$$\mu^{o}_{Al^{+}} - \mu^{o}_{\underline{Al}} + \mu^{o}_{e^{-}} = - RT \ln K_{Al^{+}}. \tag{14}$$

At first glance, Eqs. (7), (8), (11), and (12) represent a mathematical system of four equations in four unknowns that, ordinarily, could be solved by simple iteration. From the standpoint of the Gibbs phase rule, however, the chemical system under consideration, consisting of one component and two phases, enjoys but one degree of freedom. This means that at an arbitrarily fixed temperature, liquid (or solid) and vapor are in equilibrium at a unique pressure which can be determined in the following manner.

The expression for the total pressure as the sum of the partial pressures is

$$P = P_{Al} + P_{Al^{+}} + P_{e^{-}}, \tag{15}$$

where, from Eq. (11),

$$P_{Al} = K_{Al} \exp\,[(P - 1)\bar{V}_{\underline{Al}}/RT], \tag{16}$$

from Eq. (12),

$$P_{Al^+} = \{K_{Al^+} \exp\,[(P - 1)\bar{V}_{\underline{Al}}/RT]\}^{1/2}, \tag{17}$$

and, from Eq. (8),

$$P_{e^-} = P_{Al^+}. \tag{18}$$

Equations (15) through (18) can now be solved by iteration. A value of P is guessed and substituted in Eqs. (16) and (17). The process is repeated until Eq. (15) is satisfied.

III. THERMODYNAMIC EQUATIONS

The molecular weight of the gas-Al mixture is given by the relation

$$M = \frac{26.98}{\bar{n}}, \tag{19}$$

where 26.98 is the formula weight of the input material Al and $\bar{n}$ is the total number of moles in the mixture.

The specific free energy (in calories per gram) of the mixture is given by the expression

$$f = \frac{1}{26.98}\{\sum^{g} n_i[\mu_i^o + RT \ln (n_iP/n)] + n_{\underline{Al}}\,[\mu_{\underline{Al}}^o + c(P - 1)\bar{V}_{\underline{Al}}]\}, \tag{20}$$

which is derived from Eqs. (5) and (6). The summation is over all gaseous species. The constant c = 0.0242172 converts cc-atmospheres to calories.

The specific entropy (in calories per degree per gram) of the mixture is given by the expression

$$s = \frac{1}{26.98}\{\sum^{g} n_i[S_i^o - R \ln (n_iP/n)] + n_{\underline{Al}}\,[S_{\underline{Al}}^o - c\alpha_v(P - 1)\bar{V}_{\underline{Al}}]\}, \tag{21}$$

where S_i^o and $S_{\underline{Al}}^o$ are the standard molar entropy of component i and Al, respectively, at a given temperature, and α_v is the volume coefficient of thermal expansion of Al.

The specific enthalpy (in calories per gram) of the gas mixture is given by the expression

$$h = \frac{1}{26.98}\{\sum^{g} n_iH_i^o + n_{\underline{Al}}\,[H_{\underline{Al}}^o + c(1 - \alpha_vT)(P - 1)\bar{V}_{\underline{Al}}]\}, \tag{22}$$

where H_i^o and $H_{\underline{Al}}^o$ are the standard molar heat content of component i and Al, respectively, at a given temperature.

The specific internal energy (in calories per gram) of the mixture is given by the expression

$$u = \frac{1}{26.98}\left\{\sum^{g} n_i(H_i^o - RT) + n_{\underline{Al}}\left[H^o_{\underline{Al}} - c[1 + (P-1)\alpha_v T]\bar{V}_{\underline{Al}}\right]\right\} \tag{23}$$

The terms representing the increase in a thermodynamic property from one atmosphere to P atmospheres for Al, namely,

$$\Delta F = (P-1)\bar{V}_{\underline{Al}}, \tag{24}$$

$$\Delta S = -\alpha_v(P-1)\bar{V}_{\underline{Al}}, \tag{25}$$

$$\Delta H = (1 - \alpha_v T)(P-1)\bar{V}_{\underline{Al}}, \tag{26}$$

$$\Delta U = -\alpha_v T(P-1)\bar{V}_{\underline{Al}}, \tag{27}$$

are readily derived from the differential formulas relating the various thermodynamic functions. Each of the above terms must be multiplied by the factor c = 0.0242172 to convert it from cc-atmospheres to calories.

The specific volume of the mixture (in cubic centimeters per gram) is given by the expression

$$v = \frac{1}{26.98}\{nRT/P + n_{\underline{Al}}\,\bar{V}_{\underline{Al}}\}, \tag{28}$$

where the first term in the braces is the volume of the gas phase and the second term is that of the condensed phase.

IV. BASIC DATA

The pertinent thermodynamic properties (heat content, entropy, free energy, and heat of formation) for the 5 chemical species considered in this study were taken from JANAF Thermochemical Data.[1] The molecular weights and heats of formation of the various chemical species are listed in the following table.

Species	Molecular Weight	Heat of Formation at $0^{\circ}K$ (cal/mole)
Al(s)	26.98	0
Al(l)	26.98	(0)
Al(g)	26.98	77,400
Al^{+}	26.979	215,400
e^{-}	0.00054876	0

The molar volume of solid Al ($\bar{V}_{Al}$ = 10.00 cc) was derived from a mean density of 2.6989 gm/cc.

The volume coefficient of thermal expansion for aluminum is

$$\alpha_v = \frac{1}{v}\left[\frac{\partial v}{\partial T}\right]_p = 117 \times 10^{-6} \text{ cc/cc-deg.}$$

This value was derived from the linear coefficient of thermal expansion for aluminum given in Ref. 2 for the temperature range $25\text{-}800^{\circ}K$.

Two values of the gas constant were used: R = 1.98716 cal/deg-mole and R = 82.0557 cc-atm/deg-mole. Their ratio gives the conversion factor c = 0.0242172.

V. COMPUTATIONAL PROCEDURE

The two sets of equilibrium composition equations--the one involving solid or liquid Al and the other the gaseous species only--represent two mutually exclusive contiguous regions. It is expedient to determine the border line between the two regions, that is, the conditions of temperature and pressure under which the condensed species just vanishes. This can be done in the following manner.

Equation (7) may be written in the form

$$n_{\underline{Al}} = 1 - n(P_{Al} + P_{Al^+}), \tag{29}$$

where n is the total number of moles of gas in the system and P_{Al} and P_{Al^+} are the partial pressures of Al and Al^+ at an arbitrary temperature. Equation (29) can now be solved for n for any value of $n_{\underline{Al}}$ from 0 to, say, 0.99999.

VI. RESULTS

The results of this study are presented numerically in Tables 1 and 2 and graphically in Figs. 1, 2, and 3. Figure 1 is a conventional Mollier diagram for aluminum; specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight in the pure gas region, and cross plots of temperature and moles of condensed Al in the gas-liquid and gas-solid regions. The broken line demarcates the pure gas phase (above) from the fog and smoke (below). Of particular interest is the saltus experienced by the moles-of-condensed-Al isograms in traversing the 933°K-isotherm--the melting point of aluminum.

Figure 2 is a plot of volume versus temperature with cross plots of constant pressure and moles of condensed aluminum.

The variation of vaporization temperature with pressure for aluminum and graphite is shown in Fig. 3. For aluminum at 10^{-3} atm the vaporization temperature is 1801°K, at 1 atm it is 2767°K, while at 10^{2} atm it is 4419°K. The corresponding temperatures for graphite are 2968°K, 3697°K, and 4244°K.[3]

All the computations required to obtain the results in Table 1 and 2 were made on the RAND IBM 360/65 computer. In the tables the numbers are represented in "floating decimal" notation; the first five digits indicate the decimal form of the number, and the last two digits indicate a power of 10. Thus 12345 05 represents 0.12345×10^{5} and 12345-05 represents 0.12345×10^{-5}.

Table 1

SUMMARY OF COMPUTED VALUES OF VOLUME, MOLECULAR WEIGHT, MOLES OF GAS, AND MOLES OF SOLID OR LIQUID ALUMINUM FOR ALUMINUM AT VARIOUS TEMPERATURES AND PRESSURES

Temperature, T (^{O}K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
6000 04	10000-07	12562 02	13490 02	20000 01	
6000 04	10000-06	11562 02	13490 02	20000 01	
6000 04	10000-05	10562 02	13491 02	19998 01	
6000 04	10000-04	95619 01	13501 02	19983 01	
6000 04	10000-03	85586 01	13603 02	19833 01	
6000 04	10000-02	75315 01	14479 02	18634 01	
6000 04	10000-01	64303 01	18280 02	14759 01	
6000 04	10000 00	53289 01	23086 02	11687 01	
6000 04	10000 01	42841 01	25597 02	10540 01	
6000 04	10000 02	32686 01	26526 02	10171 01	
6000 04	10000 03	22636 01	26835 02	10054 01	
6000 04	68074 03	14291 01	26924 02	10021 01	22650-05
6000 04	68074 03	13840 01	26930 02	90186 00	10000 00
6000 04	68074 03	13337 01	26935 02	80166 00	20000 00
6000 04	68074 03	12768 01	26941 02	70145 00	30000 00
6000 04	68074 03	12113 01	26946 02	60124 00	40000 00
6000 04	68074 03	11341 01	26952 02	50104 00	50000 00
6000 04	68074 03	10401 01	26958 02	40083 00	60000 00
6000 04	68074 03	92002 00	26963 02	30062 00	70000 00
6000 04	68074 03	75349 00	26969 02	20041 00	80000 00
6000 04	68074 03	47997 00	26974 02	10021 00	90000 00
6000 04	68074 03	-19685 00	26979 02	10021-01	99000 00
6000 04	68074 03	-40106 00	26980 02	10021-02	99900 00
6000 04	68074 03	-42795 00	26980 02	10021-03	99990 00
6000 04	68074 03	-43073 00	26980 02	10021-04	99999 00
5500 04	10000-07	12524 02	13490 02	20000 01	
5500 04	10000-06	11524 02	13490 02	19999 01	
5500 04	10000-05	10524 02	13494 02	19994 01	
5500 04	10000-04	95232 01	13531 02	19940 01	
5500 04	10000-03	85122 01	13875 02	19445 01	
5500 04	10000-02	74468 01	16131 02	16726 01	
5500 04	10000-01	63294 01	21140 02	12762 01	
5500 04	10000 00	52611 01	24741 02	10905 01	
5500 04	10000 01	42357 01	26227 02	10287 01	
5500 04	10000 02	32274 01	26737 02	10091 01	
5500 04	10000 03	22247 01	26903 02	10029 01	
5500 04	42173 03	15990 01	26942 02	10014 01	13709-05
5500 04	42173 03	15537 01	26946 02	90126 00	10000 00
5500 04	42173 03	15031 01	26950 02	80112 00	20000 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
5500 04	42173 03	14458 01	26954 02	70098 00	30000 00
5500 04	42173 03	13798 01	26957 02	60084 00	40000 00
5500 04	42173 03	13020 01	26961 02	50070 00	50000 00
5500 04	42173 03	12071 01	26965 02	40056 00	60000 00
5500 04	42173 03	10855 01	26969 02	30042 00	70000 00
5500 04	42173 03	91595 00	26972 02	20028 00	80000 00
5500 04	42173 03	63402 00	26976 02	10014 00	90000 00
5500 04	42173 03	-11683 00	26980 02	10014-01	99000 00
5500 04	42173 03	-38722 00	26980 02	10014-02	99900 00
5500 04	42173 03	-42646 00	26980 02	10014-03	99990 00
5500 04	42173 03	-43058 00	26980 02	10014-04	99999 00
5000 04	10000-07	12483 02	13490 02	20000 01	
5000 04	10000-06	11483 02	13492 02	19997 01	
5000 04	10000-05	10482 02	13508 02	19973 01	
5000 04	10000-04	94774 01	13668 02	19740 01	
5000 04	10000-03	84386 01	14944 02	18054 01	
5000 04	10000-02	73266 01	19343 02	13948 01	
5000 04	10000-01	62369 01	23778 02	11347 01	
5000 04	10000 00	52003 01	25869 02	10429 01	
5000 04	10000 01	41879 01	26618 02	10136 01	
5000 04	10000 02	31839 01	26865 02	10043 01	
5000 04	10000 03	21826 01	26943 02	10014 01	
5000 04	23560 03	18102 01	26956 02	10009 01	17285-05
5000 04	23560 03	17648 01	26959 02	90079 00	10000 00
5000 04	23560 03	17140 01	26961 02	80071 00	20000 00
5000 04	23560 03	16564 01	26963 02	70062 00	30000 00
5000 04	23560 03	15900 01	26966 02	60053 00	40000 00
5000 04	23560 03	15117 01	26968 02	50044 00	50000 00
5000 04	23560 03	14160 01	26970 02	40035 00	60000 00
5000 04	23560 03	12931 01	26973 02	30026 00	70000 00
5000 04	23560 03	11211 01	26975 02	20018 00	80000 00
5000 04	23560 03	83210 00	26978 02	10009 00	90000 00
5000 04	23560 03	55876-02	26980 02	10009-01	99000 00
5000 04	23560 03	-36164 00	26980 02	10009-02	99900 00
5000 04	23560 03	-42358 00	26980 02	10009-03	99990 00
5000 04	23560 03	-43029 00	26980 02	10009-04	99999 00
4500 04	10000-07	12437 02	13491 02	19998 01	
4500 04	10000-06	11437 02	13501 02	19984 01	
4500 04	10000-05	10434 02	13599 02	19840 01	
4500 04	10000-04	94075 01	14447 02	18675 01	
4500 04	10000-03	83074 01	18194 02	14829 01	
4500 04	10000-02	72051 01	23024 02	11718 01	
4500 04	10000-01	61596 01	25572 02	10551 01	

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
4500 04	10000 00	51438 01	26518 02	10074 01	
4500 04	10000 01	41387 01	26832 02	10055 01	
4500 04	10000 02	31370 01	26933 02	10017 01	
4500 04	10000 03	21365 01	26965 02	10006 01	
4500 04	11430 03	20785 01	26966 02	10005 01	10133-05
4500 04	11430 03	20329 01	26967 02	90046 00	10000 00
4500 04	11430 03	19819 01	26969 02	80041 00	20000 00
4500 04	11430 03	19241 01	26970 02	70036 00	30000 00
4500 04	11430 03	18575 01	26972 02	60031 00	40000 00
4500 04	11430 03	17788 01	26973 02	50026 00	50000 00
4500 04	11430 03	16825 01	26974 02	40021 00	60000 00
4500 04	11430 03	15587 01	26976 02	30015 00	70000 00
4500 04	11430 03	13848 01	26977 02	20010 00	80000 00
4500 04	11430 03	10904 01	26979 02	10005 00	90000 00
4500 04	11430 03	19451 00	26980 02	10005-01	99000 00
4500 04	11430 03	-30974 00	26980 02	10005-02	99900 00
4500 04	11430 03	-41727 00	26980 02	10005-03	99990 00
4500 04	11430 03	-42964 00	26980 02	10005-04	99999 00
4000 04	10000-07	12386 02	13500 02	19985 01	
4000 04	10000-06	11383 02	13591 02	19852 01	
4000 04	10000-05	10358 02	14380 02	18762 01	
4000 04	10000-04	92608 01	18006 02	14984 01	
4000 04	10000-03	81566 01	22886 02	11789 01	
4000 04	10000-02	71094 01	25516 02	10574 01	
4000 04	10000-01	60930 01	26498 02	10182 01	
4000 04	10000 00	50876 01	26826 02	10057 01	
4000 04	10000 01	40859 01	26931 02	10018 01	
4000 04	10000 02	30854 01	26964 02	10006 01	
4000 04	45543 02	24268 01	26973 02	10003 01	14901-05
4000 04	45543 02	23811 01	26973 02	90024 00	10000 00
4000 04	45543 02	23301 01	26974 02	80021 00	20000 00
4000 04	45543 02	22722 01	26975 02	70019 00	30000 00
4000 04	45543 02	22054 01	26976 02	60016 00	40000 00
4000 04	45543 02	21264 01	26976 02	50013 00	50000 00
4000 04	45543 02	20298 01	26977 02	40011 00	60000 00
4000 04	45543 02	19053 01	26978 02	30008 00	70000 00
4000 04	45543 02	17302 01	26979 02	20005 00	80000 00
4000 04	45543 02	14322 01	26979 02	10003 00	90000 00
4000 04	45543 02	48271 00	26980 02	10003-01	99000 00
4000 04	45543 02	-19554 00	26980 02	10003-02	99900 00
4000 04	45543 02	-40085 00	26980 02	10003-03	99990 00
4000 04	45543 02	-42793 00	26980 02	10003-04	99999 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
3500 04	10000-07	12323 02	13655 02	19758 01	
3500 04	10000-06	11286 02	14858 02	18159 01	
3500 04	10000-05	10176 02	19170 02	14074 01	
3500 04	10000-04	90839 01	23673 02	11397 01	
3500 04	10000-03	80461 01	25829 02	10446 01	
3500 04	10000-02	70332 01	26605 02	10141 01	
3500 04	10000-01	60291 01	26860 02	10045 01	
3500 04	10000 00	50277 01	26942 02	10014 01	
3500 04	10000 01	40273 01	26968 02	10004 01	
3500 04	10000 02	30272 01	26976 02	10001 01	
3500 04	13652 02	28920 01	26977 02	10001 01	14305-05
3500 04	13652 02	28462 01	26977 02	90011 00	10000 00
3500 04	13652 02	27951 01	26977 02	80010 00	20000 00
3500 04	13652 02	27372 01	26978 02	70008 00	30000 00
3500 04	13652 02	26703 01	26978 02	60007 00	40000 00
3500 04	13652 02	25912 01	26978 02	50006 00	50000 00
3500 04	13652 02	24943 01	26979 02	40005 00	60000 00
3500 04	13652 02	23696 01	26979 02	30004 00	70000 00
3500 04	13652 02	21938 01	26979 02	20002 00	80000 00
3500 04	13652 02	18938 01	26980 02	10001 00	90000 00
3500 04	13652 02	91195 00	26980 02	10001-01	99000 00
3500 04	13652 02	60722-01	26980 02	10001-02	99900 00
3500 04	13652 02	-34815 00	26980 02	10001-03	99990 00
3500 04	13652 02	-42200 00	26980 02	10001-04	99999 00
3000 04	10000-07	12158 02	17108 02	15770 01	
3000 04	10000-06	11046 02	22150 02	12181 01	
3000 04	10000-05	99898 01	25204 02	10705 01	
3000 04	10000-04	89698 01	26391 02	10223 01	
3000 04	10000-03	79632 01	26791 02	10071 01	
3000 04	10000-02	69612 01	26920 02	10022 01	
3000 04	10000-01	59605 01	26961 02	10007 01	
3000 04	10000 00	49603 01	26974 02	10002 01	
3000 04	10000 01	39602 01	26978 02	10001 01	
3000 04	26584 01	35356 01	26979 02	10000 01	19670-05
3000 04	26584 01	34898 01	26979 02	90004 00	10000 00
3000 04	26584 01	34387 01	26979 02	80003 00	20000 00
3000 04	26584 01	33807 01	26979 02	70003 00	30000 00
3000 04	26584 01	33138 01	26979 02	60002 00	40000 00
3000 04	26584 01	32346 01	26979 02	50002 00	50000 00
3000 04	26584 01	31377 01	26980 02	40002 00	60000 00
3000 04	26584 01	30128 01	26980 02	30001 00	70000 00
3000 04	26584 01	28368 01	26980 02	20001 00	80000 00
3000 04	26584 01	25360 01	26980 02	10000 00	90000 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
3000 04	26584 01	15402 01	26980 02	10000-01	99000 00
3000 04	26584 01	58008 00	26980 02	10000-02	99900 00
3000 04	26584 01	-14640 00	26980 02	10000-03	99990 00
3000 04	26584 01	-39258 00	26980 02	10000-04	99999 00
2767 04	99969 00	39252 01	26979 02	10000 01	10729-05
2767 04	99969 00	38795 01	26979 02	90002 00	10000 00
2767 04	99969 00	38283 01	26979 02	80002 00	20000 00
2767 04	99969 00	37703 01	26980 02	70002 00	30000 00
2767 04	99969 00	37034 01	26980 02	60001 00	40000 00
2767 04	99969 00	36242 01	26980 02	50001 00	50000 00
2767 04	99969 00	35273 01	26980 02	40001 00	60000 00
2767 04	99969 00	34024 01	26980 02	30001 00	70000 00
2767 04	99969 00	32263 01	26980 02	20000 00	80000 00
2767 04	99969 00	29254 01	26980 02	10000 00	90000 00
2767 04	99969 00	19271 01	26980 02	10000-01	99000 00
2767 04	99969 00	94391 00	26980 02	10000-02	99900 00
2767 04	99969 00	83655-01	26980 02	10000-03	99990 00
2767 04	99969 00	-34216 00	26980 02	10000-04	99999 00
2500 04	10000-07	11905 02	25556 02	10557 01	
2500 04	10000-06	10889 02	26512 02	10176 01	
2500 04	10000-05	98834 01	26830 02	10056 01	
2500 04	10000-04	88818 01	26932 02	10018 01	
2500 04	10000-03	78812 01	26965 02	10006 01	
2500 04	10000-02	68811 01	26975 02	10002 01	
2500 04	10000-01	58810 01	26978 02	10001 01	
2500 04	10000 00	48810 01	26980 02	10000 01	
2500 04	25753 00	44702 01	26980 02	10000 01	14901-05
2500 04	25753 00	44244 01	26980 02	90001 00	10000 00
2500 04	25753 00	43733 01	26980 02	80001 00	20000 00
2500 04	25753 00	43153 01	26980 02	70001 00	30000 00
2500 04	25753 00	42483 01	26980 02	60001 00	40000 00
2500 04	25753 00	41692 01	26980 02	50000 00	50000 00
2500 04	25753 00	40722 01	26980 02	40000 00	60000 00
2500 04	25753 00	39473 01	26980 02	30000 00	70000 00
2500 04	25753 00	37712 01	26980 02	20000 00	80000 00
2500 04	25753 00	34702 01	26980 02	10000 00	90000 00
2500 04	25753 00	24707 01	26980 02	10000-01	99000 00
2500 04	25753 00	14756 01	26980 02	10000-02	99900 00
2500 04	25753 00	52153 00	26980 02	10000-03	99990 00
2500 04	25753 00	-17660 00	26980 02	10000-04	99999 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
2000 04	10000-07	11785 02	26944 02	10013 01	
2000 04	10000-06	10784 02	26969 02	10004 01	
2000 04	10000-05	97842 01	26976 02	10001 01	
2000 04	10000-04	87841 01	26979 02	10000 01	
2000 04	10000-03	77841 01	26980 02	10000 01	
2000 04	10000-02	67841 01	26980 02	10000 01	
2000 04	72633-02	59230 01	26980 02	10000 01	95367-06
2000 04	72633-02	58772 01	26980 02	90000 00	10000 00
2000 04	72633-02	58261 01	26980 02	80000 00	20000 00
2000 04	72633-02	57681 01	26980 02	70000 00	30000 00
2000 04	72633-02	57011 01	26980 02	60000 00	40000 00
2000 04	72633-02	56219 01	26980 02	50000 00	50000 00
2000 04	72633-02	55250 01	26980 02	40000 00	60000 00
2000 04	72633-02	54001 01	26980 02	30000 00	70000 00
2000 04	72633-02	52240 01	26980 02	20000 00	80000 00
2000 04	72633-02	49230 01	26980 02	10000 00	90000 00
2000 04	72633-02	39230 01	26980 02	10000-01	99000 00
2000 04	72633-02	29232 01	26980 02	10000-02	99900 00
2000 04	72633-02	19249 01	26980 02	10000-03	99990 00
2000 04	72633-02	94177 00	26980 02	10000-04	99999 00
1500 04	10000-07	11659 02	26980 02	10000 01	
1500 04	10000-06	10659 02	26980 02	10000 01	
1500 04	10000-05	96592 01	26980 02	10000 01	
1500 04	10000-04	86592 01	26980 02	10000 01	
1500 04	17004-04	84286 01	26980 02	10000 01	47684-06
1500 04	17004-04	83828 01	26980 02	90000 00	10000 00
1500 04	17004-04	83317 01	26980 02	80000 00	20000 00
1500 04	17004-04	82737 01	26980 02	70000 00	30000 00
1500 04	17004-04	82068 01	26980 02	60000 00	40000 00
1500 04	17004-04	81276 01	26980 02	50000 00	50000 00
1500 04	17004-04	80307 01	26980 02	40000 00	60000 00
1500 04	17004-04	79057 01	26980 02	30000 00	70000 00
1500 04	17004-04	77296 01	26980 02	20000 00	80000 00
1500 04	17004-04	74286 01	26980 02	10000 00	90000 00
1500 04	17004-04	64286 01	26980 02	10000-01	99000 00
1500 04	17004-04	54286 01	26980 02	10000-02	99900 00
1500 04	17004-04	44286 01	26980 02	10000-03	99990 00
1500 04	17004-04	34287 01	26980 02	10000-04	99999 00
1000 04	74458-10	13611 02	26980 02	10000 01	53644-06
1000 04	74458-10	13565 02	26980 02	90000 00	10000 00
1000 04	74458-10	13514 02	26980 02	80000 00	20000 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
1000 04	74458-10	13456 02	26980 02	70000 00	30000 00
1000 04	74458-10	13389 02	26980 02	60000 00	40000 00
1000 04	74458-10	13310 02	26980 02	50000 00	50000 00
1000 04	74458-10	13213 02	26980 02	40000 00	60000 00
1000 04	74458-10	13088 02	26980 02	30000 00	70000 00
1000 04	74458-10	12912 02	26980 02	20000 00	80000 00
1000 04	74458-10	12611 02	26980 02	10000 00	90000 00
1000 04	74458-10	11611 02	26980 02	10000-01	99000 00
1000 04	74458-10	10611 02	26980 02	10000-02	99900 00
1000 04	74458-10	96112 01	26980 02	10000-03	99990 00
1000 04	74458-10	86112 01	26980 02	10000-04	99999 00
9330 03	50967-11	14746 02	26980 02	10000 01	53644-06
9330 03	50967-11	14700 02	26980 02	90000 00	10000 00
9330 03	50967-11	14649 02	26980 02	80000 00	20000 00
9330 03	50967-11	14591 02	26980 02	70000 00	30000 00
9330 03	50967-11	14524 02	26980 02	60000 00	40000 00
9330 03	50967-11	14445 02	26980 02	50000 00	50000 00
9330 03	50967-11	14348 02	26980 02	40000 00	60000 00
9330 03	50967-11	14223 02	26980 02	30000 00	70000 00
9330 03	50967-11	14047 02	26980 02	20000 00	80000 00
9330 03	50967-11	13746 02	26980 02	10000 00	90000 00
9330 03	50967-11	12746 02	26980 02	10000-01	99000 00
9330 03	50967-11	11746 02	26980 02	10000-02	99900 00
9330 03	50967-11	10746 02	26980 02	10000-03	99990 00
9330 03	50967-11	97457 01	26980 02	10000-04	99999 00
9330 03	50961-11	14746 02	26980 02	10000 01	53644-06
9330 03	50961-11	14700 02	26980 02	90000 00	10000 00
9330 03	50961-11	14649 02	26980 02	80000 00	20000 00
9330 03	50961-11	14591 02	26980 02	70000 00	30000 00
9330 03	50961-11	14524 02	26980 02	60000 00	40000 00
9330 03	50961-11	14445 02	26980 02	50000 00	50000 00
9330 03	50961-11	14348 02	26980 02	40000 00	60000 00
9330 03	50961-11	14223 02	26980 02	30000 00	70000 00
9330 03	50961-11	14047 02	26980 02	20000 00	80000 00
9330 03	50961-11	13746 02	26980 02	10000 00	90000 00
9330 03	50961-11	12746 02	26980 02	10000-01	99000 00
9330 03	50961-11	11746 02	26980 02	10000-02	99900 00
9330 03	50961-11	10746 02	26980 02	10000-03	99990 00
9330 03	50961-11	97457 01	26980 02	10000-04	99999 00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Al
9000 03	11135-11	15391 02	26980 02	10000 01	53644-06
9000 03	11135-11	15345 02	26980 02	90000 00	10000 00
9000 03	11135-11	15294 02	26980 02	80000 00	20000 00
9000 03	11135-11	15236 02	26980 02	70000 00	30000 00
9000 03	11135-11	15169 02	26980 02	60000 00	40000 00
9000 03	11135-11	15090 02	26980 02	50000 00	50000 00
9000 03	11135-11	14993 02	26980 02	40000 00	60000 00
9000 03	11135-11	14868 02	26980 02	30000 00	70000 00
9000 03	11135-11	14692 02	26980 02	20000 00	80000 00
9000 03	11135-11	14391 02	26980 02	10000 00	90000 00
9000 03	11135-11	13391 02	26980 02	10000-01	99000 00
9000 03	11135-11	12391 02	26980 02	10000-02	99900 00
9000 03	11135-11	11391 02	26980 02	10000-03	99990 00
9000 03	11135-11	10391 02	26980 02	10000-04	99999 00
4419 04	10000 03	21286 01	26967 02	10005 01	10926-05
3392 04	10000 02	30135 01	26978 02	10001 01	18319-05
2767 04	10000 01	39251 01	26979 02	10000 01	10730-05
2344 04	10000 00	48530 01	26980 02	10000 01	20668-05
2036 04	10000-01	57919 01	26980 02	10000 01	11956-05
1802 04	10000-02	67388 01	26980 02	10000 01	10390-05
1617 04	10000-03	76919 01	26980 02	10000 01	93001-06
1468 04	10000-04	86499 01	26980 02	10000 01	48583-06
1344 04	10000-05	96116 01	26980 02	10000 01	78646-06
1240 04	10000-06	10577 02	26980 02	10000 01	89371-06
1151 04	10000-07	11544 02	26980 02	10000 01	67791-06
1075 04	10000-08	12514 02	26980 02	10000 01	52741-06
1008 04	10000-09	13486 02	26980 02	10000 01	53417-06
9490 03	10000-10	14460 02	26980 02	10000 01	54255-06

Table 2

SUMMARY OF COMPUTED VALUES OF DENSITY, ENTHALPY, ENERGY, AND ENTROPY FOR ALUMINUM AT VARIOUS TEMPERATURES AND PRESSURES

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
6000 04	10000-07	27400-12	10198 05	93140 04	54342 01
6000 04	10000-06	27400-11	10198 05	93139 04	50950 01
6000 04	10000-05	27402-10	10197 05	93130 04	47557 01
6000 04	10000-04	27423-09	10187 05	93042 04	44150 01
6000 04	10000-03	27630-08	10095 05	92181 04	40615 01
6000 04	10000-02	29409-07	93508 04	85273 04	36084 01
6000 04	10000-01	37130-06	69487 04	62964 04	29222 01
6000 04	10000 00	46891-05	50439 04	45275 04	23840 01
6000 04	10000 01	51991-04	43333 04	38675 04	20788 01
6000 04	10000 02	53878-03	41044 04	36549 04	18657 01
6000 04	10000 03	54505-02	40319 04	35876 04	16823 01
6000 04	68074 03	37228-01	40112 04	35683 04	15370 01
6000 04	68074 03	41301-01	37823 04	33832 04	14989 01
6000 04	68074 03	46375-01	35535 04	31980 04	14608 01
6000 04	68074 03	52870-01	33247 04	30128 04	14226 01
6000 04	68074 03	61481-01	30958 04	28277 04	13845 01
6000 04	68074 03	73442-01	28670 04	26425 04	13463 01
6000 04	68074 03	91182-01	26381 04	24573 04	13082 01
6000 04	68074 03	12022 00	24093 04	22722 04	12701 01
6000 04	68074 03	17640 00	21804 04	20870 04	12319 01
6000 04	68074 03	33116 00	19516 04	19018 04	11938 01
6000 04	68074 03	15734 01	17457 04	17352 04	11595 01
6000 04	68074 03	25180 01	17251 04	17185 04	11560 01
6000 04	68074 03	26789 01	17230 04	17168 04	11557 01
6000 04	68074 03	26961 01	17228 04	17167 04	11556 01
5500 04	10000-07	29891-12	10011 05	92010 04	54018 01
5500 04	10000-06	29892-11	10011 05	92007 04	50625 01
5500 04	10000-05	29900-10	10007 05	91976 04	47228 01
5500 04	10000-04	29981-09	99745 04	91668 04	43780 01
5500 04	10000-03	30745-08	96717 04	88841 04	39876 01
5500 04	10000-02	35742-07	80099 04	73323 04	33741 01
5500 04	10000-01	46842-06	55871 04	50701 04	26856 01
5500 04	10000 00	54820-05	44518 04	40101 04	22812 01
5500 04	10000 01	58112-04	40741 04	36574 04	20338 01
5500 04	10000 02	59244-03	39541 04	35453 04	18395 01
5500 04	10000 03	59611-02	39161 04	35098 04	16621 01
5500 04	42173 03	25177-01	39071 04	35014 04	15542 01
5500 04	42173 03	27945-01	36745 04	33091 04	15120 01
5500 04	42173 03	31398-01	34420 04	31167 04	14697 01

Table 2--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
5500 04	42173 03	35823-01	32094 04	29243 04	14274 01
5500 04	42173 03	41702-01	29769 04	27320 04	13851 01
5500 04	42173 03	49888-01	27444 04	25396 04	13428 01
5500 04	42173 03	62073-01	25118 04	23473 04	13006 01
5500 04	42173 03	82134-01	22793 04	21549 04	12583 01
5500 04	42173 03	12135 00	20467 04	19626 04	12160 01
5500 04	42173 03	23226 00	18142 04	17702 04	11737 01
5500 04	42173 03	13087 01	16049 04	15971 04	11357 01
5500 04	42173 03	24391 01	15840 04	15798 04	11319 01
5500 04	42173 03	26697 01	15819 04	15781 04	11315 01
5500 04	42173 03	26951 01	15817 04	15779 04	11314 01
5000 04	10000-07	32881-12	98256 04	90891 04	53664 01
5000 04	10000-06	32885-11	98242 04	90877 04	50269 01
5000 04	10000-05	32924-10	98096 04	90740 04	46850 01
5000 04	10000-04	33314-09	96690 04	89421 04	43195 01
5000 04	10000-03	36424-08	86537 04	79869 04	37921 01
5000 04	10000-02	47146-07	61804 04	56667 04	30252 01
5000 04	10000-01	57956-06	46132 04	41954 04	25007 01
5000 04	10000 00	63053-05	40608 04	36767 04	22070 01
5000 04	10000 01	64879-04	38840 04	35107 04	19977 01
5000 04	10000 02	65479-03	38280 04	34582 04	18155 01
5000 04	10000 03	65671-02	38103 04	34416 04	16420 01
5000 04	23560 03	15480-01	38075 04	34389 04	15782 01
5000 04	23560 03	17189-01	35708 04	32388 04	15309 01
5000 04	23560 03	19322-01	33341 04	30388 04	14835 01
5000 04	23560 03	22060-01	30974 04	28388 04	14362 01
5000 04	23560 03	25701-01	28607 04	26387 04	13889 01
5000 04	23560 03	30783-01	26240 04	24387 04	13415 01
5000 04	23560 03	38369-01	23873 04	22386 04	12942 01
5000 04	23560 03	50917-01	21506 04	20386 04	12468 01
5000 04	23560 03	75662-01	19140 04	18385 04	11995 01
5000 04	23560 03	14720 00	16773 04	16385 04	11522 01
5000 04	23560 03	98722 00	14642 04	14585 04	11096 01
5000 04	23560 03	22995 01	14429 04	14405 04	11053 01
5000 04	23560 03	26520 01	14408 04	14387 04	11049 01
5000 04	23560 03	26933 01	14406 04	14385 04	11048 01
4500 04	10000-07	36536-12	96402 04	89773 04	53273 01
4500 04	10000-06	36563-11	96314 04	89691 04	49863 01
4500 04	10000-05	36829-10	95460 04	88884 04	46292 01
4500 04	10000-04	39125-09	88551 04	82361 04	41461 01
4500 04	10000-03	49271-08	65734 04	60819 04	33522 01
4500 04	10000-02	67354-07	47274 04	43390 04	27204 01
4500 04	10000-01	69253-06	40347 04	36851 04	23794 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
4500 04	10000 00	71815-05	38115 04	34743 04	21546 01
4500 04	10000 01	72666-04	37407 04	34075 04	19676 01
4500 04	10000 02	72940-03	37184 04	33863 04	17925 01
4500 04	10000 03	73027-02	37113 04	33797 04	16211 01
4500 04	11430 03	83470-02	37111 04	33795 04	16112 01
4500 04	11430 03	92713-02	34699 04	31714 04	15576 01
4500 04	11430 03	10426-01	32288 04	29633 04	15040 01
4500 04	11430 03	11909-01	29876 04	27552 04	14504 01
4500 04	11430 03	13883-01	27465 04	25471 04	13969 01
4500 04	11430 03	16643-01	25053 04	23390 04	13433 01
4500 04	11430 03	20771-01	22642 04	21309 04	12897 01
4500 04	11430 03	27624-01	20230 04	19228 04	12361 01
4500 04	11430 03	41225-01	17819 04	17147 04	11825 01
4500 04	11430 03	81209-01	15407 04	15066 04	11289 01
4500 04	11430 03	63899 00	13237 04	13193 04	10807 01
4500 04	11430 03	20405 01	13020 04	13006 04	10759 01
4500 04	11430 03	26138 01	12998 04	12987 04	10754 01
4500 04	11430 03	26893 01	12996 04	12986 04	10753 01
4000 04	10000-07	41131-12	94480 04	88593 04	52820 01
4000 04	10000-06	41406-11	93704 04	87856 04	49244 01
4000 04	10000-05	43812-10	87336 04	81809 04	44350 01
4000 04	10000-04	54858-09	65267 04	60852 04	35941 01
4000 04	10000-03	69728-08	46600 04	43127 04	29038 01
4000 04	10000-02	77738-07	39503 04	36388 04	25386 01
4000 04	10000-01	80733-06	37212 04	34213 04	23060 01
4000 04	10000 00	81730-05	36486 04	33523 04	21164 01
4000 04	10000 01	82051-04	36257 04	33305 04	19405 01
4000 04	10000 02	82153-03	36184 04	33236 04	17689 01
4000 04	45543 02	37427-02	36166 04	33219 04	16568 01
4000 04	45543 02	41579-02	33708 04	31056 04	15953 01
4000 04	45543 02	46767-02	31250 04	28892 04	15339 01
4000 04	45543 02	53435-02	28792 04	26728 04	14724 01
4000 04	45543 02	62320-02	26334 04	24565 04	14110 01
4000 04	45543 02	74750-02	23876 04	22401 04	13495 01
4000 04	45543 02	93373-02	21418 04	20237 04	12881 01
4000 04	45543 02	12435-01	18961 04	18074 04	12266 01
4000 04	45543 02	18610-01	16503 04	15910 04	11652 01
4000 04	45543 02	36966-01	14045 04	13746 04	11037 01
4000 04	45543 02	32907 00	11833 04	11799 04	10484 01
4000 04	45543 02	15687 01	11611 04	11604 04	10429 01
4000 04	45543 02	25168 01	11589 04	11585 04	10423 01
4000 04	45543 02	26787 01	11587 04	11583 04	10423 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
3500 04	10000-07	47547-12	91334 04	86241 04	51969 01
3500 04	10000-06	51735-11	82138 04	77457 04	46089 01
3500 04	10000-05	66747-10	58655 04	55026 04	36635 01
3500 04	10000-04	82428-09	43259 04	40321 04	30111 01
3500 04	10000-03	89935-08	37789 04	35097 04	26711 01
3500 04	10000-02	92636-07	36038 04	33423 04	24469 01
3500 04	10000-01	93526-06	35483 04	32894 04	22601 01
3500 04	10000 00	93811-05	35308 04	32726 04	20850 01
3500 04	10000 01	93901-04	35252 04	32673 04	19137 01
3500 04	10000 02	93930-03	35235 04	32656 04	17436 01
3500 04	13652 02	12824-02	35233 04	32655 04	17206 01
3500 04	13652 02	14248-02	32728 04	30407 04	16490 01
3500 04	13652 02	16028-02	30222 04	28160 04	15774 01
3500 04	13652 02	18316-02	27717 04	25912 04	15058 01
3500 04	13652 02	21367-02	25212 04	23664 04	14343 01
3500 04	13652 02	25636-02	22706 04	21417 04	13627 01
3500 04	13652 02	32037-02	20201 04	19169 04	12911 01
3500 04	13652 02	42699-02	17695 04	16921 04	12195 01
3500 04	13652 02	63998-02	15190 04	14673 04	11479 01
3500 04	13652 02	12769-01	12684 04	12426 04	10763 01
3500 04	13652 02	12248 00	10430 04	10403 04	10119 01
3500 04	13652 02	86952 00	10204 04	10200 04	10055 01
3500 04	13652 02	22292 01	10182 04	10180 04	10048 01
3500 04	13652 02	26424 01	10179 04	10178 04	10048 01
3000 04	10000-07	69497-12	66954 04	63470 04	44265 01
3000 04	10000-06	89980-11	46643 04	43951 04	35156 01
3000 04	10000-05	10238-09	38293 04	35927 04	30454 01
3000 04	10000-04	10721-08	35569 04	33310 04	27779 01
3000 04	10000-03	10883-07	34705 04	32480 04	25772 01
3000 04	10000-02	10936-06	34431 04	32217 04	23978 01
3000 04	10000-01	10952-05	34345 04	32134 04	22251 01
3000 04	10000 00	10958-04	34318 04	32108 04	20546 01
3000 04	10000 01	10959-03	34309 04	32099 04	18847 01
3000 04	26584 01	29135-03	34307 04	32098 04	18126 01
3000 04	26584 01	32372-03	31754 04	29765 04	17275 01
3000 04	26584 01	36418-03	29200 04	27433 04	16423 01
3000 04	26584 01	41620-03	26647 04	25100 04	15572 01
3000 04	26584 01	48555-03	24093 04	22767 04	14721 01
3000 04	26584 01	58264-03	21540 04	20435 04	13870 01
3000 04	26584 01	72825-03	18986 04	18102 04	13019 01
3000 04	26584 01	97093-03	16433 04	15770 04	12168 01
3000 04	26584 01	14561-02	13879 04	13437 04	11316 01
3000 04	26584 01	29107-02	11326 04	11105 04	10465 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
3000 04	26584 01	28827-01	90276 03	90052 03	96992 00
3000 04	26584 01	26298 00	87978 03	87953 03	96226 00
3000 04	26584 01	14009 01	87748 03	87743 03	96149 00
3000 04	26584 01	24694 01	87725 03	87722 03	96142 00
2767 04	99969 00	11879-03	33877 04	31839 04	18696 01
2767 04	99969 00	13199-03	31301 04	29467 04	17765 01
2767 04	99969 00	14849-03	28725 04	27095 04	16834 01
2767 04	99969 00	16970-03	26149 04	24722 04	15903 01
2767 04	99969 00	19798-03	23573 04	22350 04	14972 01
2767 04	99969 00	23757-03	20997 04	19978 04	14041 01
2767 04	99969 00	29696-03	18421 04	17606 04	13111 01
2767 04	99969 00	39593-03	15845 04	15233 04	12180 01
2767 04	99969 00	59385-03	13269 04	12861 04	11249 01
2767 04	99969 00	11874-02	10693 04	10489 04	10318 01
2767 04	99969 00	11827-01	83744 03	83539 03	94797 00
2767 04	99969 00	11379 00	81425 03	81404 03	93959 00
2767 04	99969 00	82479 00	81193 03	81190 03	93875 00
2767 04	99969 00	21987 01	81170 03	81169 03	93867 00
2500 04	10000-07	12458-11	36485 04	34541 04	33399 01
2500 04	10000-06	12924-10	34366 04	32492 04	30799 01
2500 04	10000-05	13079-09	33695 04	31843 04	28817 01
2500 04	10000-04	13129-08	33482 04	31638 04	27031 01
2500 04	10000-03	13145-07	33415 04	31573 04	25306 01
2500 04	10000-02	13150-06	33394 04	31552 04	23601 01
2500 04	10000-01	13151-05	33387 04	31546 04	21902 01
2500 04	10000 00	13152-04	33385 04	31544 04	20206 01
2500 04	25753 00	33871-04	33385 04	31543 04	19509 01
2500 04	25753 00	37634-04	30783 04	29125 04	18468 01
2500 04	25753 00	42338-04	28181 04	26708 04	17427 01
2500 04	25753 00	48386-04	25579 04	24290 04	16386 01
2500 04	25753 00	56450-04	22977 04	21872 04	15346 01
2500 04	25753 00	67740-04	20375 04	19454 04	14305 01
2500 04	25753 00	84675-04	17773 04	17037 04	13264 01
2500 04	25753 00	11290-03	15171 04	14619 04	12223 01
2500 04	25753 00	16934-03	12570 04	12201 04	11183 01
2500 04	25753 00	33967-03	99676 03	97835 03	10142 01
2500 04	25753 00	33828-02	76260 03	76075 03	92053 00
2500 04	25753 00	33451-01	73918 03	73899 03	91116 00
2500 04	25753 00	30093 00	73684 03	73682 03	91027 00
2500 04	25753 00	15018 01	73660 03	73660 03	91013 00

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
2000 04	10000-07	16418-11	32535 04	31060 04	31703 01
2000 04	10000-06	16433-10	32485 04	31012 04	29981 01
2000 04	10000-05	16438-09	32470 04	30997 04	28277 01
2000 04	10000-04	16439-08	32465 04	30992 04	26579 01
2000 04	10000-03	16440-07	32463 04	30990 04	24882 01
2000 04	10000-02	16440-06	32463 04	30990 04	23186 01
2000 04	72633-02	11941-05	32463 04	30990 04	21725 01
2000 04	72633-02	13268-05	29812 04	28487 04	20400 01
2000 04	72633-02	14926-05	27162 04	25983 04	19075 01
2000 04	72633-02	17059-05	24512 04	23481 04	17750 01
2000 04	72633-02	19902-05	21861 04	20978 04	16425 01
2000 04	72633-02	23882-05	19211 04	18475 04	15099 01
2000 04	72633-02	29852-05	16561 04	15972 04	13774 01
2000 04	72633-02	39803-05	13910 04	13469 04	12449 01
2000 04	72633-02	59705-05	11260 04	10966 04	11124 01
2000 04	72633-02	11941-04	86098 03	84625 03	97988 00
2000 04	72633-02	11940-03	62246 03	62098 03	86062 00
2000 04	72633-02	11936-02	59860 03	59846 03	84869 00
2000 04	72633-02	11888-01	59622 03	59620 03	84750 00
2000 04	72633-02	11435 00	59598 03	59598 03	84738 00
1500 04	10000-07	21920-11	31541 04	30436 04	31135 01
1500 04	10000-06	21920-10	31541 04	30436 04	29439 01
1500 04	10000-05	21920-09	31541 04	30436 04	27743 01
1500 04	10000-04	21920-08	31541 04	30436 04	26047 01
1500 04	17004-04	37273-08	31541 04	30436 04	25656 01
1500 04	17004-04	41415-08	28842 04	27848 04	23857 01
1500 04	17004-04	46591-08	26144 04	25260 04	22058 01
1500 04	17004-04	53247-08	23445 04	22671 04	20259 01
1500 04	17004-04	62122-08	20746 04	20083 04	18460 01
1500 04	17004-04	74546-08	18047 04	17495 04	16660 01
1500 04	17004-04	93183-08	15348 04	14906 04	14861 01
1500 04	17004-04	12424-07	12650 04	12318 04	13062 01
1500 04	17004-04	18637-07	99508 03	97299 03	11263 01
1500 04	17004-04	37273-07	72521 03	71416 03	94637 00
1500 04	17004-04	37273-06	48232 03	48121 03	78445 00
1500 04	17004-04	37273-05	45803 03	45792 03	76826 00
1500 04	17004-04	37273-04	45560 03	45559 03	76664 00
1500 04	17004-04	37268-03	45536 03	45535 03	76647 00
1000 04	74458-10	24482-13	30619 04	29882 04	33996 01
1000 04	74458-10	27202-13	27872 04	27209 04	31249 01
1000 04	74458-10	30602-13	25125 04	24535 04	28502 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
1000 04	74458-10	34974-13	22377 04	21862 04	25755 01
1000 04	74458-10	40803-13	19630 04	19188 04	23008 01
1000 04	74458-10	48964-13	16883 04	16515 04	20260 01
1000 04	74458-10	61205-13	14136 04	13841 04	17513 01
1000 04	74458-10	81606-13	11389 04	11168 04	14766 01
1000 04	74458-10	12241-12	86414 03	84941 03	12019 01
1000 04	74458-10	24482-12	58942 03	58206 03	92716 00
1000 04	74458-10	24482-11	34218 03	34144 03	67992 00
1000 04	74458-10	24482-10	31745 03	31738 03	65519 00
1000 04	74458-10	24482-09	31498 03	31497 03	65272 00
1000 04	74458-10	24482-08	31473 03	31473 03	65247 00
9330 03	50967-11	17961-14	30495 04	29808 04	35843 01
9330 03	50967-11	19957-14	27742 04	27123 04	32892 01
9330 03	50967-11	22452-14	24988 04	24438 04	29941 01
9330 03	50967-11	25659-14	22234 04	21753 04	26989 01
9330 03	50967-11	29936-14	19481 04	19068 04	24038 01
9330 03	50967-11	35923-14	16727 04	16383 04	21086 01
9330 03	50967-11	44904-14	13973 04	13698 04	18135 01
9330 03	50967-11	59872-14	11220 04	11013 04	15184 01
9330 03	50967-11	89807-14	84659 03	83285 03	12232 01
9330 03	50967-11	17961-13	57123 03	56436 03	92807 00
9330 03	50967-11	17961-12	32340 03	32271 03	66245 00
9330 03	50967-11	17961-11	29862 03	29855 03	63588 00
9330 03	50967-11	17961-10	29614 03	29613 03	63323 00
9330 03	50967-11	17961-09	29589 03	29589 03	63296 00
9330 03	50961-11	17959-14	30495 04	29808 04	35843 01
9330 03	50961-11	19955-14	27647 04	27028 04	32790 01
9330 03	50961-11	22449-14	24798 04	24248 04	29737 01
9330 03	50961-11	25656-14	21950 04	21469 04	26684 01
9330 03	50961-11	29932-14	19101 04	18689 04	23631 01
9330 03	50961-11	35919-14	16253 04	15909 04	20578 01
9330 03	50961-11	44898-14	13404 04	13129 04	17525 01
9330 03	50961-11	59864-14	10555 04	10349 04	14472 01
9330 03	50961-11	89796-14	77069 03	75694 03	11419 01
9330 03	50961-11	17959-13	48583 03	47896 03	83655 00
9330 03	50961-11	17959-12	22946 03	22878 03	56177 00
9330 03	50961-11	17959-11	20383 03	20376 03	53430 00
9330 03	50961-11	17959-10	20126 03	20126 03	53155 00
9330 03	50961-11	17959-09	20101 03	20101 03	53127 00

Table 2--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Density, d (gm/cc)	Entnalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
9000 03	11135-11	40681-15	30434 04	29771 04	36897 01
9000 03	11135-11	45201-15	27582 04	26985 04	33728 01
9000 03	11135-11	50851-15	24730 04	24200 04	30559 01
9000 03	11135-11	58115-15	21878 04	21414 04	27390 01
9000 03	11135-11	67801-15	19025 04	18628 04	24220 01
9000 03	11135-11	81361-15	16173 04	15842 04	21051 01
9000 03	11135-11	10170-14	13321 04	13056 04	17882 01
9000 03	11135-11	13560-14	10468 04	10270 04	14713 01
9000 03	11135-11	20340-14	76162 03	74836 03	11544 01
9000 03	11135-11	40681-14	47640 03	46977 03	83745 00
9000 03	11135-11	40681-13	21969 03	21903 03	55223 00
9000 03	11135-11	40681-12	19402 03	19396 03	52370 00
9000 03	11135-11	40681-11	19146 03	19145 03	52085 00
9000 03	11135-11	40681-10	19120	19120 03	52057 00
4419 04	10000 03	74369-02	36957 04	33701 04	16176 01
3392 04	10000 02	96938-03	35032 04	32533 04	17377 01
2767 04	10000 01	11883-03	33877 04	31839 04	18696 01
2344 04	10000 00	14029-04	33096 04	31370 04	20086 01
2036 04	10000-01	16148-05	32529 04	31030 04	21522 01
1802 04	10000-02	18247-06	32097 04	30770 04	22993 01
1617 04	10000-03	20328-07	31757 04	30566 04	24490 01
1468 04	10000-04	22395-08	31482 04	30401 04	26007 01
1344 04	10000-05	24456-09	31254 04	30264 04	27541 01
1240 04	10000-06	26514-10	31063 04	30149 04	29089 01
1151 04	10000-07	28566-11	30899 04	30050 04	30648 01
1075 04	10000-08	30605-12	30758 04	29965 04	32217 01
1008 04	10000-09	32628-13	30634 04	29891 04	33794 01
9490 03	10000-10	34645-14	30525 04	29826 04	35378 01

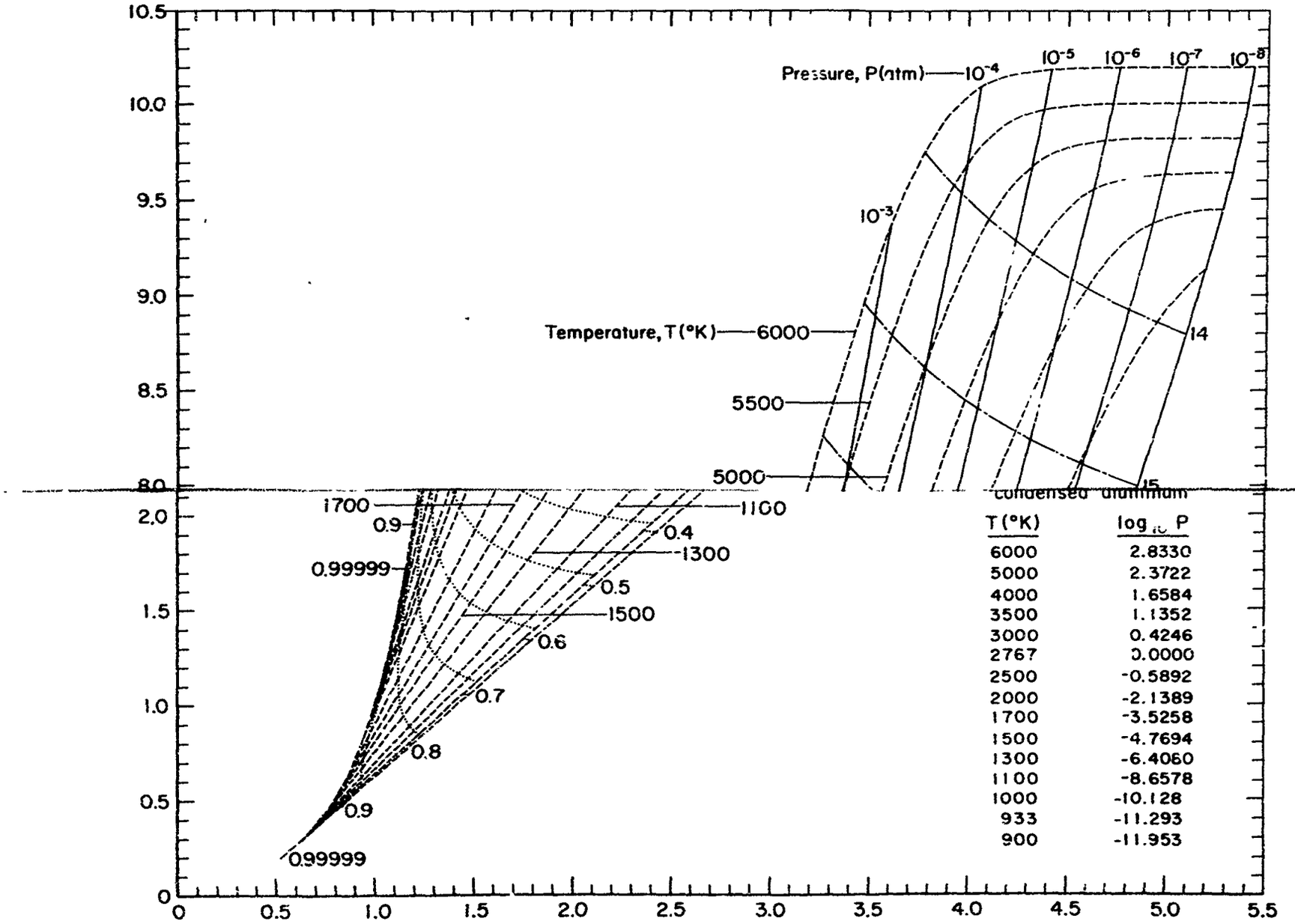
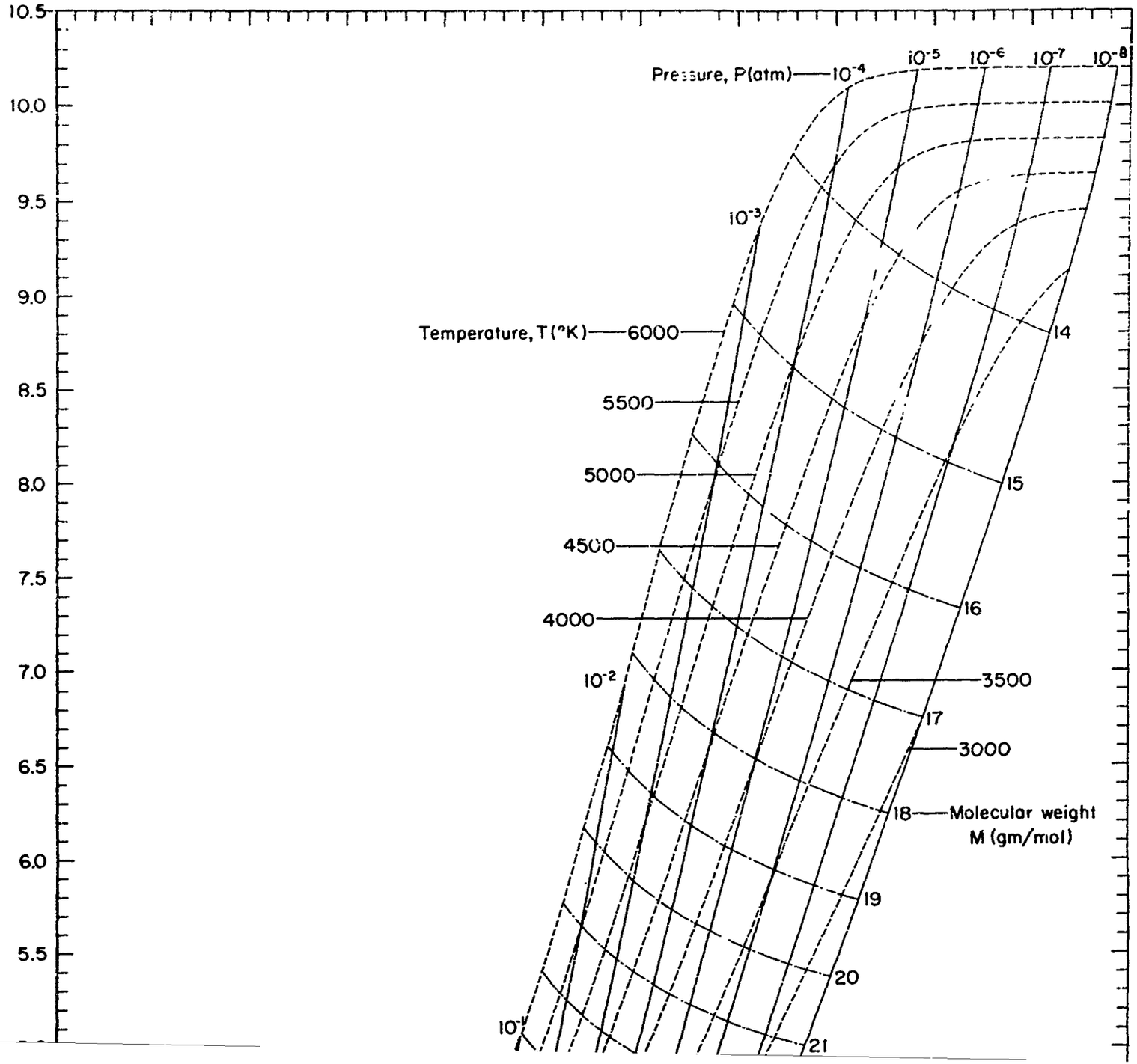


Fig. 1—Enthalpy versus entropy for aluminum with cross plots of constant temperature, pressure, molecular weight, and moles of condensed aluminum


Pressure, P(atm)
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10^-5
10^-6
10^-7
10^-8
10^-3
10^-2
10^-1
Temperature, T(°K)
6000
5500
5000
4500
4000
3500
3000
14
15
16
17
18
19
20
21
Molecular weight
M (gm/mol)
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5

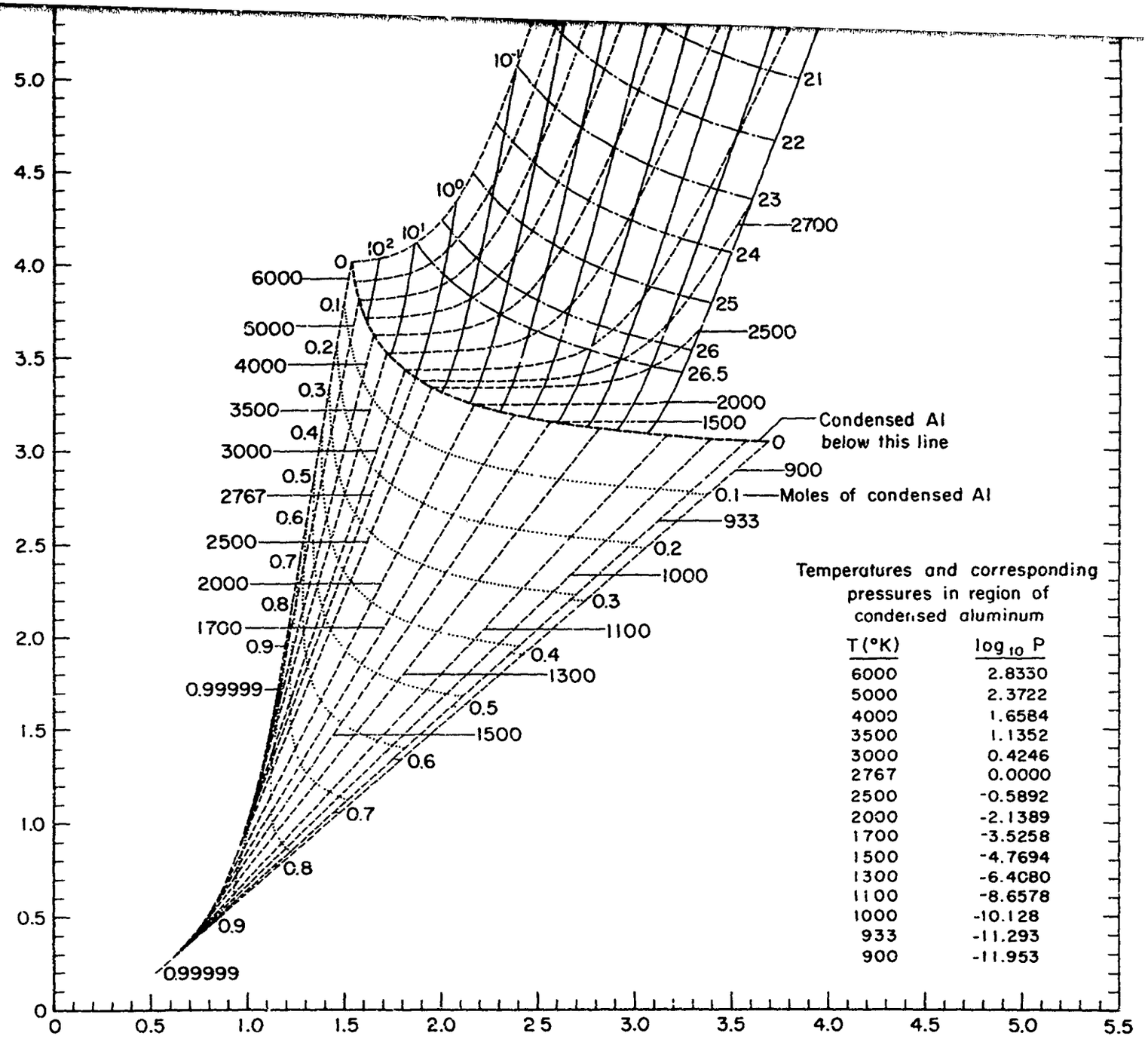

Fig. 1—Enthalpy versus entropy for aluminum with cross plots of constant temperature, pressure, molecular weight, and moles of condensed aluminum

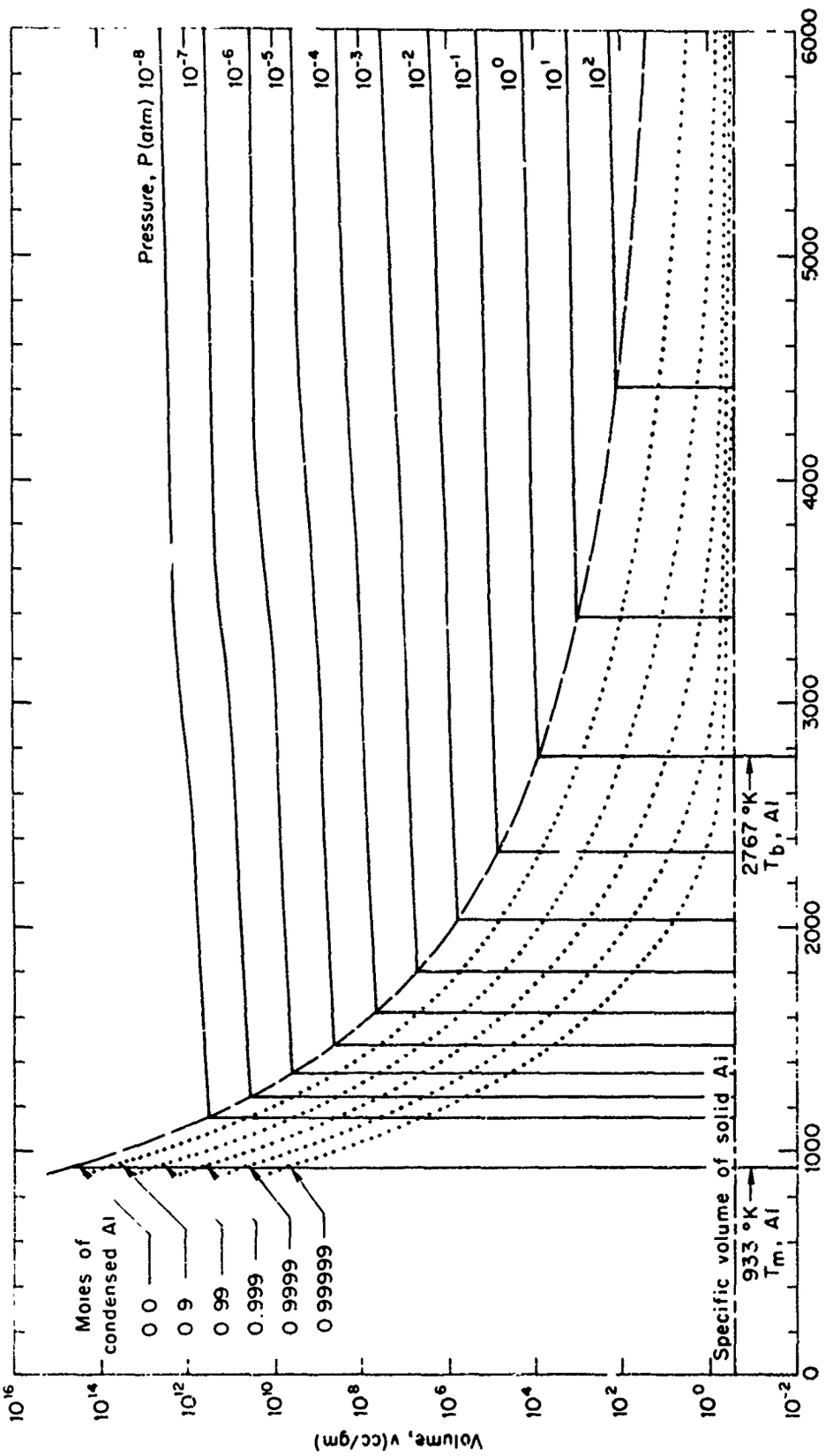

Fig. 2— Volume versus temperature for aluminum with cross plots of constant pressure and moles of condensed aluminum

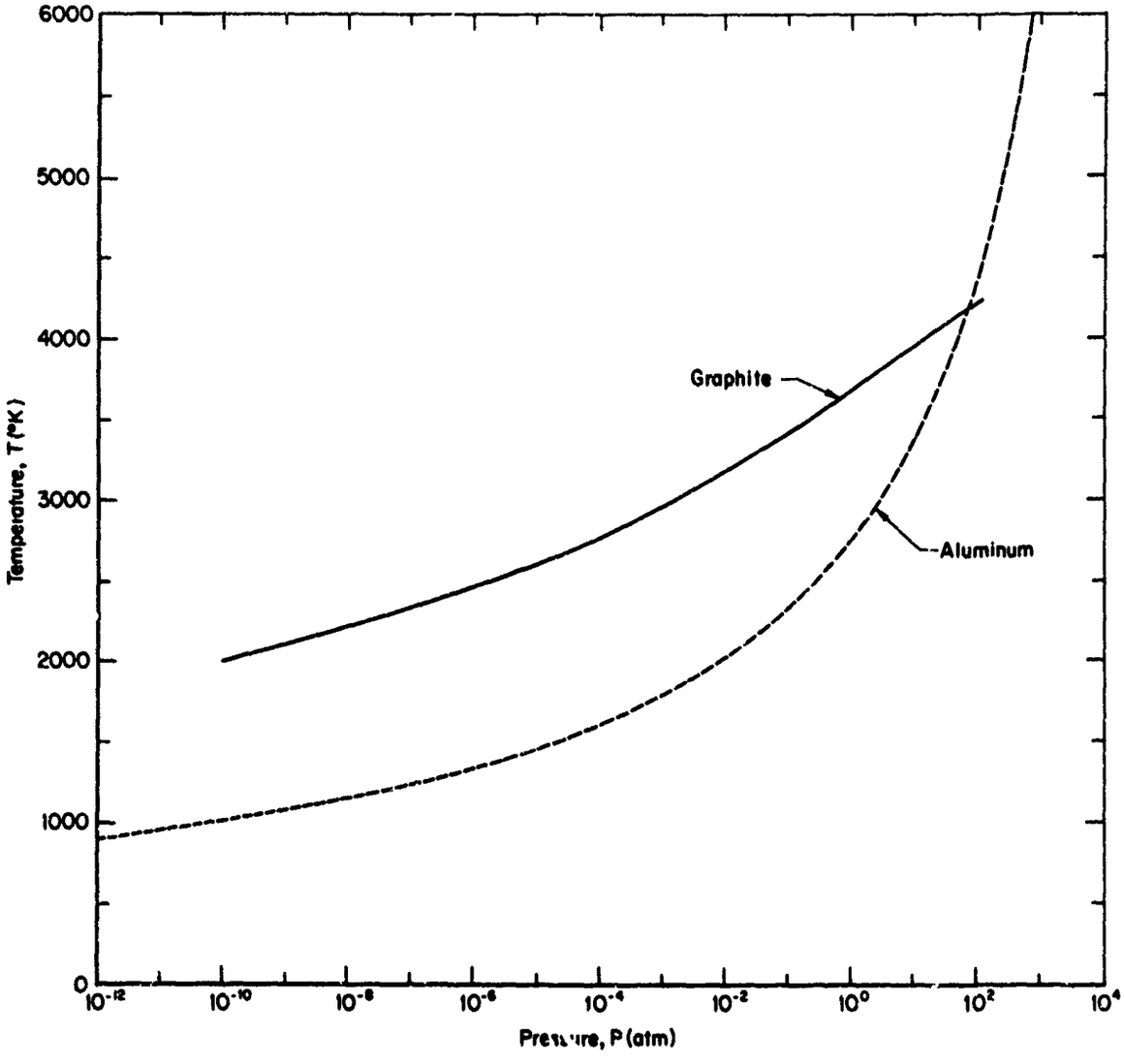

Fig. 3—Vapor pressure of aluminum and graphite

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3. Krieger, F. J., The Thermodynamics of the Graphite/Carbon Vapor System, The RAND Corporation, RM-3326-3-PR, October 1969.

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10. ABSTRACT

The 18th in a series of mathematical investigations of the thermodynamics of ablative materials, ~~this~~ study considers aluminum over a range of temperatures up to 6000 deg K and pressures up to 1000 atmospheres. Two sets of equilibrium equations are used--one representing a pure gas phase, the other a heterogeneous system of gas and condensed solid or liquid aluminum. The gas phase of the heterogenous chemical system, like the homogenous gas phase, comprises 3 gaseous species. Computational results are presented in both tabular and graphic form. The latter comprises (a) a conventional Mollier diagram in which specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight or moles of condensed aluminum; (b) a plot of volume versus temperature for aluminum; and (c) a plot of vaporization temperature for aluminum and graphite at various pressures.

11. KEY WORDS

Physics
Chemistry
Thermodynamics
Fluid Dynamics
Gas Dynamics